

Received: 02 August 2024 • Revised: 01 November 2024 • Accepted: 26 November 2024

Research

doi: 10.22034/jcema.2024.217334

Development and Characterization of SBS-Modified Bitumen for Compliance with Standards in South Asian Pavement Engineering

Md Jahidul Islam *

Department of Civil Engineering, Ahsanullah University of Science and Technology, Dhaka, Bangladesh.

* Correspondence should be addressed to Md Jahidul Islam, Department of Civil Engineering, Ahsanullah University of Science and Technology, Dhaka, Bangladesh. Email: jahidul@bclgroup.com

ABSTRACT

This research investigates the development of Polymer Modified Bitumen (PMB) to meet PG 76-18 specifications, essential for durable pavements in South Asian climates. The study evaluates the properties of raw 60/70 grade bitumen and PMB formulations with varying Styrene-Butadiene-Styrene (SBS) polymer contents (4.5%, 4.75%, 5%, and 5.5%). Among these, the PMB with 4.75% SBS polymer was identified as the most effective, demonstrating superior performance in Dynamic Shear Rheometer (DSR) tests and improved durability and stability after aging processes simulated by the Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV). Atomic Force Microscopy (AFM) further revealed microstructural improvements in phase structure and surface morphology due to aging. The 4.75% SBS polymer blend strikes an optimal balance between mechanical robustness and economic viability when combined with 60/70 grade bitumen. This formulation shows promise for modifying bitumen in South Asian regions, particularly those subject to extreme temperature variations, offering a sustainable solution for pavement construction in such climates.

Keywords: Polymer-modified bitumen, dynamic shear rheometer, styrene-butadiene-styrene, aging resistance, atomic force microscopy

Copyright © 2024, Md Jahidul Islam. This is an open access paper distributed under the [Creative Commons Attribution License](#). Journal of Civil Engineering and Materials Application is published by [ISNet](#); Journal p-ISSN 2676-332X; Journal e-ISSN 2588-2880.

1. INTRODUCTION

The road construction industry continuously seeks advancements in materials and technologies to improve the performance and longevity of asphalt pavements. One such approach gaining increasing interest is the use of polymer-modified bitumen, with Styrene-Butadiene-Styrene (SBS) being a prominent polymer modifier. By incorporating SBS into bitumen blends, engineers can significantly enhance the mechanical properties and aging resistance of asphalt pavements. The Performance Grade (PG) grading system, developed by the Strategic Highway Research Program (SHRP),

plays a crucial role in selecting appropriate bitumen grades for specific road applications. The PG system categorizes bitumen based on temperature susceptibility and performance characteristics, allowing engineers to choose bitumen grades that best match the prevailing environmental and traffic conditions. Extensive research has been conducted to understand the effects of different SBS polymer contents on bitumen blends and their performance attributes. Additional studies have evaluated the chemical properties of various polymers, especially SBS, to determine the appropriate PG bitumen grade

for specific environmental conditions and temperature.

Airey [1] compared the performance of EVA and SBS polymer-modified bitumen (PMBs) in flexible asphalt pavements, finding improved rutting and fatigue performance compared to unmodified bitumen, with implications for selecting formulations to enhance pavement durability, despite a lack of direct correlation between predicted binder performance and actual mixture performance. Zorn et al. [2] highlighted the effectiveness of various polymers, including SBS, SBR, EVA, and PPA, in improving the rheological properties of bitumen, with SBS demonstrating superior potential due to its elastomeric nature and unique microstructure, enhancing mechanical properties and rheological behavior by interacting preferentially with maltene and asphaltene components. Kumar et al. [3] investigated the enhancement of viscoelastic behavior in bituminous binders through the addition of elastomeric SBS copolymer, specifically in PG58 and PG64 grades, resulting in improved rheological properties and resistance to permanent deformation. The study of Shih et al. [4] examines how peroxide crosslinking affects the structure and mechanical properties of SBS, PS, and SBR foams, showing that higher dicumyl peroxide concentrations lead to smaller, denser cells and increased foam density, resulting in improved mechanical performance. Saboo et al. [5] explored the rheological properties of bitumen through steady-shear and dynamic analysis, utilizing rheograms and Carreau-Yasuda equations to establish temperature-independent master curves, highlighting the limitations of traditional viscometry methods, and demonstrating the applicability of the Cox-Merz rule, with implications for improved temperature prediction and mixing efficiency in modified binders. Ishaq et al. [6] evaluated the correlation between rutting susceptibility of bitumen and asphalt mixtures using various laboratory tests, highlighting J_{nr} as a superior indicator of rutting performance for asphalt materials, while $G^*/\sin\delta$ shows good correlation with permanent deformation of asphalt groups prepared using similar binders. Oluwasola et al. [7] investigated the impact of ethylene vinyl acetate (EVA) modification on the physical and rheological properties of 80-100 grade bitumen, finding that 5% EVA content enhances binder properties to levels comparable to PG 76 binder, thus improving pavement performance. Solouki et al. [8] explored the impact of blending

speed on the rheological properties of bitumen with Sasobit, finding that higher speeds lead to increased viscosity, softening point temperatures, and complex modulus values, indicating partial aging of the binder and potential reduction in pavement service life. Oner et al. [9] investigated the effects of incorporating warm-mix asphalt (WMA) additives into elastomeric polymer-modified bitumen (PMB), finding that the use of organic WMA additives enhances rutting performance, particularly in PMB with 4% SBS copolymer concentration, while conventional properties indicate reduced temperature susceptibility. Oner et al. [9] investigates the impact of oxidative aging on the chemical and rheological properties of neat and SBS polymer-modified bitumen, establishing aging indexes based on chemical and rheological properties, and evaluating aging characteristics using various analytical techniques such as FT-IR, TLC-FID, and DSR. Vargas et al. [10] examines chemically-grafted polyethylene as asphalt modifiers, finding increased softening point and decreased penetration degree in blends, improved rutting resistance and time-temperature-dependent response, and enhanced miscibility with asphalt compared to non-grafted polyethylene blends, with zero shear viscosity models assessed for predicting rutting behavior. Kaya et al. [11] investigated the rheological behavior of SBS modified bitumen under varying shear rate and mixing time conditions, indicating that higher shear rates and longer mixing times promote oxidative aging and higher activation energies for flow and temperature susceptibility, while maintaining similar compatibility levels between SBS and bitumen at constant shear rate and mixing time. Liu et al. [12] investigated the impact of rheometer gap size on rheological properties of bitumen binders, revealing a relationship where smaller gap sizes lead to decreased complex modulus, with modifiers and bitumen type influencing the effect, and proposes the Temperature-Gap Superposition Principle (TGSP) to relate complex moduli measured at different states. Airey et al. [13] investigated linearity limits and rheological properties of various unmodified and modified bituminous binders, along with asphalt mixtures, using dynamic shear rheometer (DSR) and dynamic uniaxial tension-compression apparatus, revealing strain-dependent linearity criteria and unique rheological characteristics of elastomeric modified binders in particular. Two high polymer mixtures

(HPM) were placed at the 2009 National Center for Asphalt Technology (NCAT) Test Track as part of a field trial, and laboratory test results indicated that HPM mixtures can be used to develop more efficient (i.e., thinner) pavement cross-sections due to their enhanced fatigue and rutting resistance [14]. In a comprehensive laboratory study investigating the properties and morphology of modified bitumen containing styrene-butadiene-styrene (SBS) and ethylene vinyl acetate (EVA) copolymers and assessing the impact of polymer content on the mechanical performance of hot-mix asphalt (HMA) compared to base bitumen [15]. The impact of reclaimed asphalt pavement (RAP) on the rheological properties of a polymer-modified binder and the fatigue cracking performance of asphalt mixtures was investigated in a study, revealing that increased stiffness in the binder was observed with higher RAP content, while reduced fatigue life and poorer fatigue cracking performance were caused in the asphalt mixtures [16]. The effect of additives, such as hydrated lime and elastomeric (SBS) and plastomeric (EVA) polymer modified bitumen (PMB), on the moisture susceptibility of hot mix asphalt (HMA) containing different types of aggregate was evaluated in research, with improved water damage resistance observed in samples prepared with hydrated lime addition and SBS PMB, compared to those with EVA PMB [17]. Bernier et al. [18] studied on rutting susceptibility of polymer-modified asphalt mixtures containing Reclaimed Asphalt Pavement (RAP) were presented in a paper, showing that the addition of RAP binder led to reduced rutting, particularly for less-modified binders, while highly modified binders were the least affected, and aggregate properties of the RAP mix also influenced the rutting results. Sengoz et al. [19] assessed SBS PMB samples, finding polymer modification enhanced conventional and mechanical properties of base bitumen. Polymer dispersion varied with content, reducing short- and long-term aging in hot-mix asphalt. Joohari et al. [20] investigated the mechanical and rheological properties of hybrid polymer-modified bitumen (PMB) using a combination of nine different polymers, demonstrating enhanced viscoelastic behavior compared to single-polymer PMBs [20]. Zhu et al. reviewed [21] 40 years of bitumen polymer modification for road construction, discussing

history, popular polymers, drawbacks, technical advances, and the importance of functionalization for enhancing polymer properties. It suggests future research should focus on adhesion, long-term performance, and recyclability. A study reviewed the effect of various polymers, including SBS, SBR, EVA, and PPA, on bitumen's rheological properties, emphasizing SBS's potential for improving mechanical behavior and exploring the interactions of maltene and asphaltene with SBS to enhance polymer-modified binders [22]. In the last three decades, researchers have extensively explored the composition-performance-microstructure relationship in asphalt, primarily leveraging atomic force microscopy (AFM) to analyze asphalt microstructure, leading to the development of evaluation criteria and modification techniques [23]. Their review highlights AFM's key role in studying asphalt aging, regeneration, and modification while promoting its wider use and standardization, ultimately facilitating a deeper understanding of the microstructure's impact on asphalt macro performance [23]. keya Ozdemir et al. [24]

Atomic Force Microscopy (AFM) was used to explore how different processing parameters and SBS modifications affect the morphology and phase structure of bitumen. Increasing mixing time and speed improved phase contrast and reduced 'bumblebee' structures. However, at the lowest speed (1000 rpm), SBS absorption was less effective, and longer mixing times (45 min) significantly changed the blend's morphology, shortening 'bumblebee' structures.

This study aims to develop and validate a Polymer Modified Bitumen (PMB) blend with a specific Styrene-Butadiene-Styrene (SBS) polymer percentage, tailored to meet performance grade (PG) specifications not commonly adopted in South Asian regions. By employing Atomic Force Microscopy (AFM) for microstructural analysis and assessing performance through Dynamic Shear Rheometer (DSR) tests and aging simulations, this research seeks to pioneer the use of a specified PG grade, thereby enhancing road durability and economic efficiency. The objective is to establish this PG grade as a new standard for robust, cost-effective road materials in South Asia, providing a contribution to regional civil engineering practices.

2. Materials and Methods of Experimentation

2.1. Performance Grade Selection

The maximum pavement surface temperature T_{sur} was found in Rajasthan at 77.1°C, and the maximum pavement temperature at 20 mm depth (TD) was recorded in the North Central Province at 63.9°C. T_{sur} and (TD) were determined using equations from the study by Rajapaksha M. et al. [25] for numerical thermal analysis. The required data, such as maximum and minimum temperatures of 36 different locations in South Asia, especially India, Bangladesh, and Sri Lanka, were collected from various sources including the LTPPBind specifying agency, Plantmaps.com, and AccuWeather, among others, for this analysis [26–29].

For slow traffic—where the average traffic speed ranges from 20 to 70 km/h—design ESALs (million) are between 10 and 30 [30]. For a stationary vehicle, when the maximum temperature at a 20 mm depth is 63.9°C, the total target temperature according to AASHTO M 323 [30] is calculated by adding 6°C twice to 63.9°C, resulting in 75.9°C, which is approximately 76°C. Therefore, a Polymer Modified Binder (PMB) was developed to satisfy the PG 76-18 criteria, ensuring resilience against the demographic variables and climatic conditions, particularly temperature fluctuations, prevalent in South Asian nations such as Bangladesh, India, and Sri Lanka.

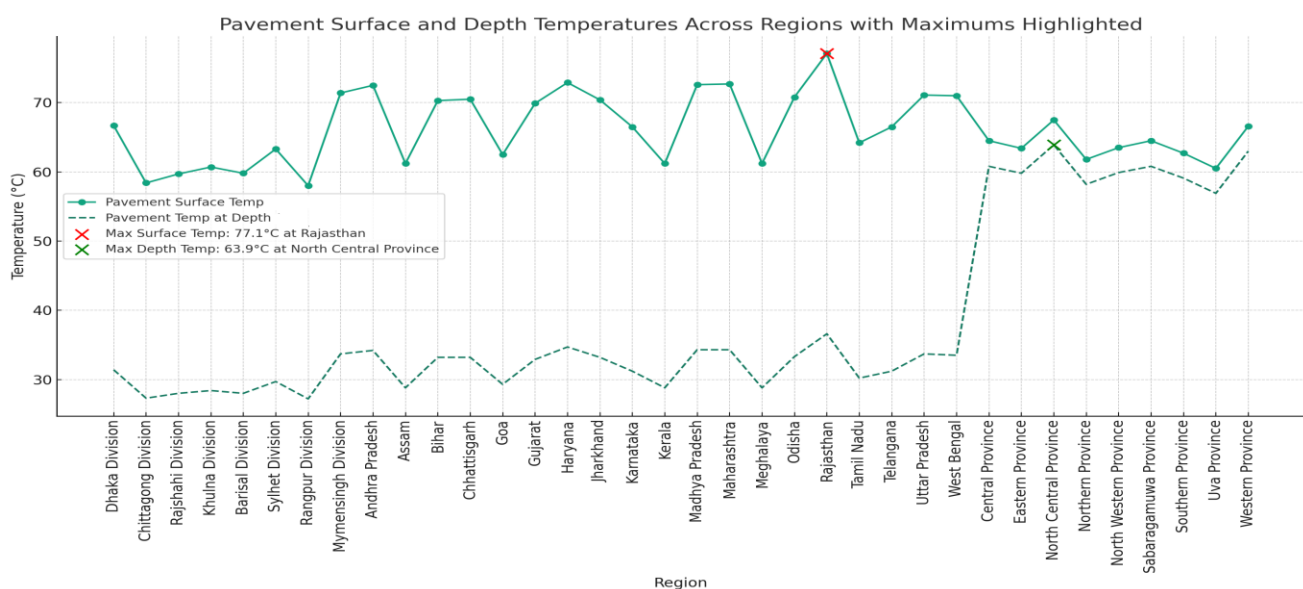


Figure 1. Maximum temperature of surface and at 100 mm depth of flexible pavement till 2024 in some major states and provenances of Bangladesh India and Sri Lanka.

2.2. Experimentation & Standard Provisions

A comprehensive overview of the testing and analysis conducted, encompassing penetration, softening point tests to assess hardness and consistency, elastic recovery tests to evaluate deformation resistance under traffic loads, and dynamic shear rheological tests (DSR or BBR) utilizing the conduit DSR to determine the complex modulus and phase angle of the bitumen blends. We use the test results to identify the polymer content that satisfied the requirements for the specific PG grade. The test provisions of the American Association of State Highway and Transportation Officials (AASHTO) were followed for laboratory investigations. The standard test codes that have been conducted in the laboratory for this experiment are mentioned in [Table 1](#). Test results are evaluated

according to the standard provision, M-320 of "standard specification for transportation materials and method of sampling and testing" and the manual we followed to verify the performance graded asphalt cement is AASHTO R 29-08. The tests for the experiments were carried out in a lab associated with the GDSUTP project on the N-3 national highway between Dhaka and Mymensingh, Bangladesh and some other tests were carried out at BRRL, Bangladesh. Several tests, i.e., penetration test, softening point test, flash point test, ductility test, etc., were carried out on the original samples to understand the consistency and basic properties of the original 60/70 asphalt cement. 4 numbers of polymer content i.e., 4.5, 4.75, 5.0 & 5.5 % were mixed with the raw bitumen by high shear mixing

machine are shown in [Figure 4 \(h & I\)](#). Smear tests are done during blending to check the smoothness of the blend, as shown in [Figure 4 \(a and b\)](#). Procured specified 60/70 grade bitumen was mixed with SBS polymer in different percentages with a high share mixing machine, as shown in [Figure 4 \(b\)](#), and then the required amount of sulfur (0.05 to 0.1%) was added to the mixture with a high share mixing machine for a certain period, as shown in [Figure 4](#)

2.3. Base Bitumen

Malaysian 60/70 penetration grade bitumen, processed under strict quality controls in Malaysia, is derived from crude oil through distillation and further treatment to meet specific standards. In [Figure 2](#) we can see the Molecular Structures of 60-70 Penetration Grade Bitumen. Characterized by a penetration grade of 60/70, this medium-hard bitumen is ideal for a variety of temperatures and traffic conditions. It is primarily used in road construction for hot mix

[\(c\)](#). The mixture is then blended using a low shear mixing machine for one and a half hours at a speed of 500 to 600 rpm while maintaining a temperature of 120°C to 130 °C, as shown in [Figure 4 \(d\)](#). After that, the mixture is stored in an airtight container. And then some RTFO residue was subjected to PAV for 24 hours. PAV residue samples were then subjected to the DSR test again to determine $G^*/\sin\delta$ parameters.

asphalt and for manufacturing bituminous waterproofing products like roofing felt. Offering excellent durability and resistance to deformation under load, its flexibility accommodates temperature fluctuations, thereby reducing the risk of cracking.. The necessary tests required for this base bitumen are detailed in [Table 1](#), alongside the standard provisions.

2.4. Polymer Used as Modifier

Poly(styrene-butadiene-styrene), commonly referred to as SBS, is a versatile block copolymer with a unique structure that imparts specific mechanical and chemical properties. Its backbone consists of three

distinct segments, making it an A-B-A block copolymer. In [Figure 2](#) we can see the chemical structure of the SBS polymer.

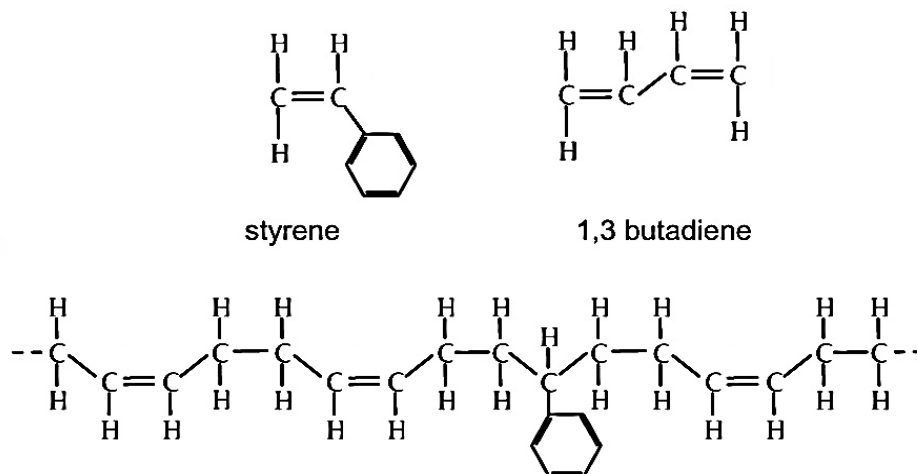


Figure 2. Chemical structure of Styrene-Butadiene-Styrene.



Figure 3. a) SBS Blending Smear Test showing incomplete blending representative; b) SBS Blending Smear Test showing complete homogenized blending representative c) sulfur addition to PMB for cross-linking representative; d) Slow mixing setup representative; e) RTFO test; f) PAV test; g) DSR test.; h) SBS addition during high shear blending representative. i) High shear mixing at 180 °C representative.

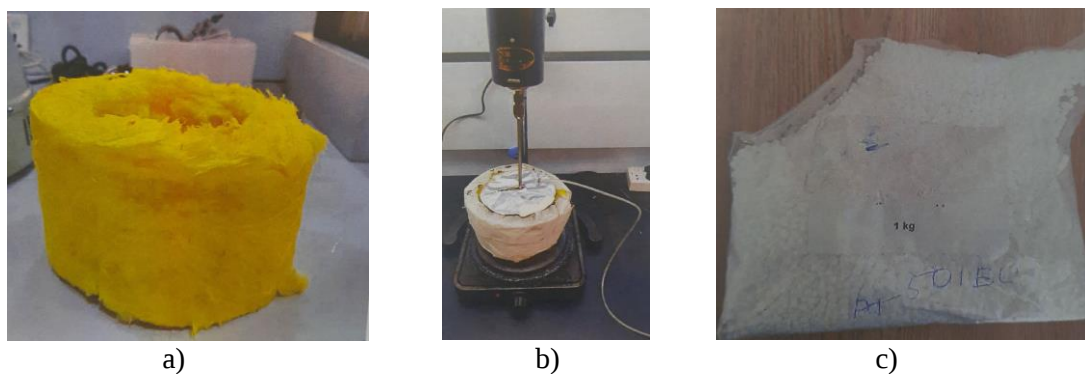


Figure 4. a) Heating jacket: Representative b) Blending setup representative; c) Representative SBS sample (pellet).

In [Figure 2](#) the first segment is composed of polystyrene, which is a rigid and glassy thermoplastic with good dimensional stability. The middle segment comprises polybutadiene, a highly flexible and elastomeric material known for its resilience and impact resistance. The third segment of [Figure 2](#) consists of another polystyrene section, contributing to SBS's overall rigidity. This segmented structure allows SBS to exhibit a balance of properties from both polystyrene and polybutadiene. The hard-polystyrene segments contribute to its durability, stiffness, and resistance to heat, while the soft polybutadiene segments provide elasticity and flexibility. An SBS Sample was sourced from China with Styrene-Butadiene ratio of 30:70 ([Figure 4-c](#)). It is white in color and has a tri block chain of copolymer Styrene-Butadiene-Styrene. Bitumen Grade selection: The Malaysian 60/70 penetration grade bitumen used for testing was collected from GDSUTP-BRT. This choice is crucial as the physical and chemical specifications of the asphalt directly influence the addition ratio of the polymer. The rotational viscometer measures the torque required to keep a cylindrical spindle submerged in a bitumen specimen rotating at a constant speed. This

measurement is used to determine the viscosity of the bitumen. The rotational viscometer can assess changed bitumen binders, unlike the capillary viscometers employed with the viscosity-graded approach. Bitumen binders' viscosities can be tested between 0.01 Pa s (0.1 poise) and 200 Pa s (2000 poise). The Asphalt Institute advises performing the initial viscosity measurement at 135°C and the subsequent measurement at 165°C. The base and modified bitumen's underwent viscosity tests using a Brookfield viscometer (DV-III). [Figure 4](#) illustrates three key components of the SBS-modified bitumen preparation process. Part (a) shows the heating jacket, used to maintain the bitumen at a consistent, elevated temperature during processing to ensure optimal viscosity for blending. [Figure 4 \(b\)](#) features the blending setup, equipped with the necessary machinery to achieve a homogeneous mixture, which is essential for the uniform distribution of SBS within the bitumen. Lastly, [Figure 4 \(c\)](#) presents a typical SBS pellet, the form in which the styrene-butadiene-styrene is added to the bitumen. This image highlights the physical appearance and size of the polymer modifier before integration into the bitumen matrix.

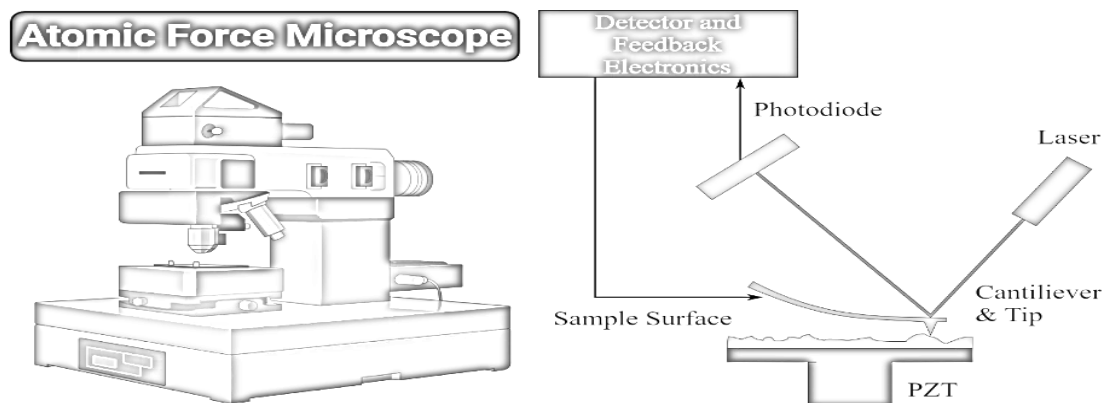


Figure 5. Schematic of an Atomic Force Microscope (AFM) detailing its core components for nanoscale analysis.

Atomic Force Microscopy (AFM) was employed to analyze the surface and mechanical properties of Polymer Modified Bitumen (PMB), specifically PG76 asphalt containing 4.75% Styrene-Butadiene-Styrene (SBS). In [Figure 5](#) we can see a diagram of an Atomic Force Microscope (AFM), highlighting its setup and key components including the cantilever, laser, and photodiode, essential for nanoscale surface analysis. AFM provided high-resolution imaging of the microstructure, enabling detailed observation of surface characteristics such as texture, roughness, and microscale phase distribution. This technique was crucial for identifying the presence of distinct

bumblebee-like structures indicative of polymer crosslinking, which are essential for understanding the material's mechanical behavior. Furthermore, AFM was instrumental in assessing the effects of aging, conducted under specific conditions (1200 hours at 60°C and 2.1 megapascals of air pressure), by documenting changes in the microstructure that influence the durability and performance of the asphalt. The quantitative data gathered from AFM analysis also aided in evaluating the PMB's modulus of elasticity and viscoelastic properties, thereby contributing significantly to the optimization of PMB formulations for enhanced road performance.

3. RESULTS AND DISCUSSION

This research provides a comprehensive evaluation of Styrene-Butadiene-Styrene (SBS) modified bitumen, aiming to meet the Performance Grade (PG) 76-18 specifications and addressing the climatic challenges of South Asia. Extensive tests, including

Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR), and Atomic Force Microscopy (AFM), have been utilized to explore the enhanced properties of bitumen for potential improvements in road durability and performance.

3.1. Physical and Chemical Properties

3.1.1. Softening Point, Penetration, and Ductility

The raw bitumen displayed favourable properties with a softening point of 52°C, penetration of 62 mm, and ductility of 110 cm (Table 1). These metrics are

within the standard limits, indicating the base bitumen's suitability for typical road conditions.

3.1.2. Flash Point and Viscosity

As shown in Table 1, the flash point and viscosity of bitumen increase with rising SBS content, reflecting enhanced thermal stability and resistance to flow. For example, bitumen with 5.5% SBS achieves a flash point of 350°C and a viscosity of 1923 cP at 135°C, significantly outperforming the unmodified sample. Figure 6(a) illustrates a positive linear relationship between SBS content and flash point, emphasizing improved thermal stability. Similarly, Figure 6 (b)

demonstrates that viscosity at 135°C increases with SBS content, indicating better high-temperature performance. In Figure 6 (c), a comparable positive trend is observed at 165°C, though the increase is less pronounced due to the higher temperature. These results underline the effectiveness of SBS modification in enhancing the bitumen's durability and operational temperature range.

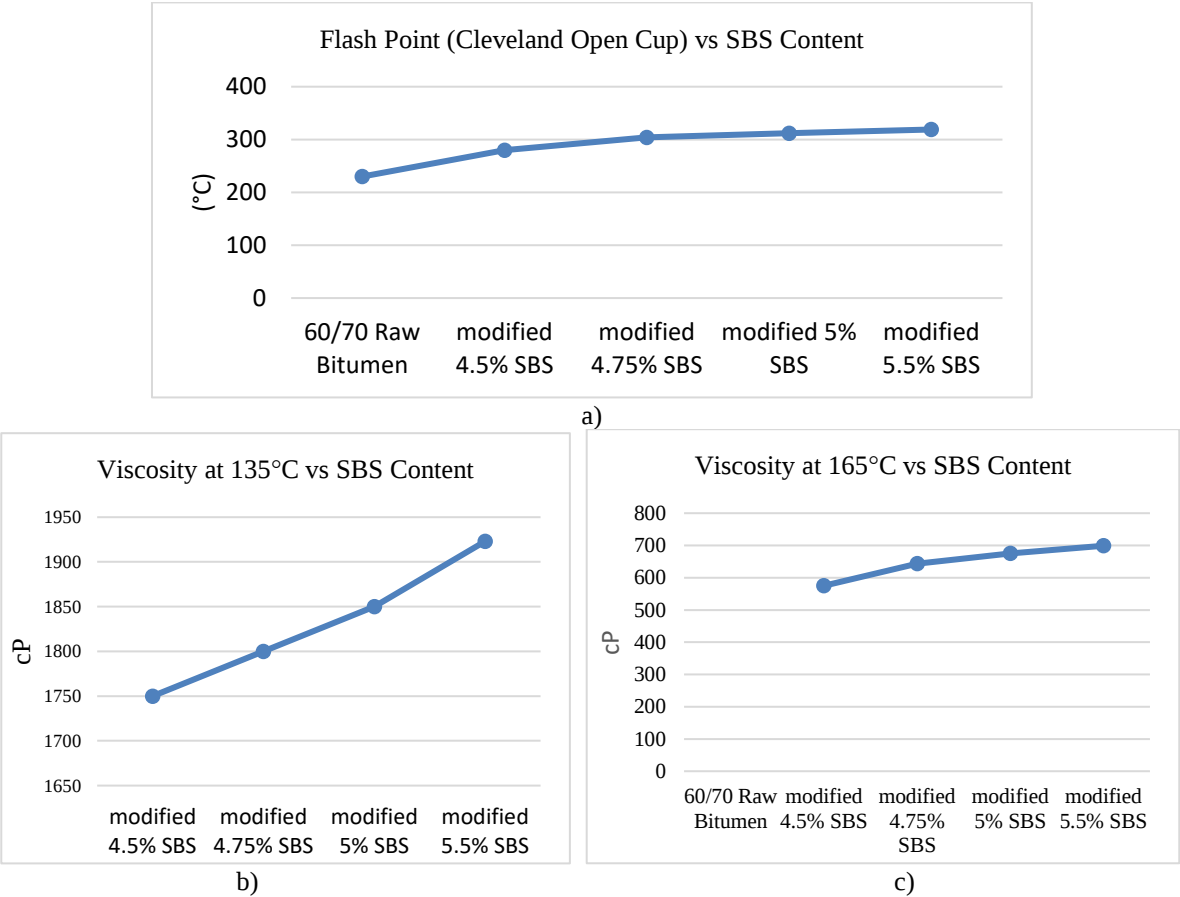


Figure 6. a) Variation of Flash Point with SBS Content in Bitumen; b) Effect of SBS Content on Bitumen Viscosity at 135°C"; c) Effect of SBS Content on Bitumen Viscosity at 165°C

3.1.3. Dynamic Shear Rheometer (DSR) Testing

The DSR tests demonstrated that bitumen's ability to withstand high-temperature and high-stress conditions improved with higher SBS content. For example, the dynamic shear modulus at 76°C for the

sample with 5% SBS was 1.95 kPa, exceeding the specified limit of 1 kPa and showing better performance than the raw bitumen.

3.2. Aging Resistance Testing

3.2.1. Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) Tests

The samples showed stable properties in the aging tests, indicating their durability. The bitumen with 5.5% SBS exhibited the least mass change in RTFO testing (0.13%) and a lower dynamic shear modulus in PAV residue testing (3456 kPa), suggesting it is less susceptible to long-term aging effects. From [Figure 7 a](#), we observe that after the RTFO aging process, the Dynamic Shear Modulus (DSR) values continue to increase with SBS content, though the increase is less significant than in the original bitumen. This shows that SBS-modified bitumen

retains better stiffness after aging, improving its resistance to rutting over time. From [Figure 7 b](#), after the Pressure Aging Vessel (PAV) test, the DSR values of modified bitumen show a decrease in shear modulus as SBS content increases. This means SBS-modified bitumen maintains more flexibility even after long-term aging. This flexibility is crucial as it prevents excessive stiffening, which could lead to cracking, thus improving the long-term performance of the bitumen.

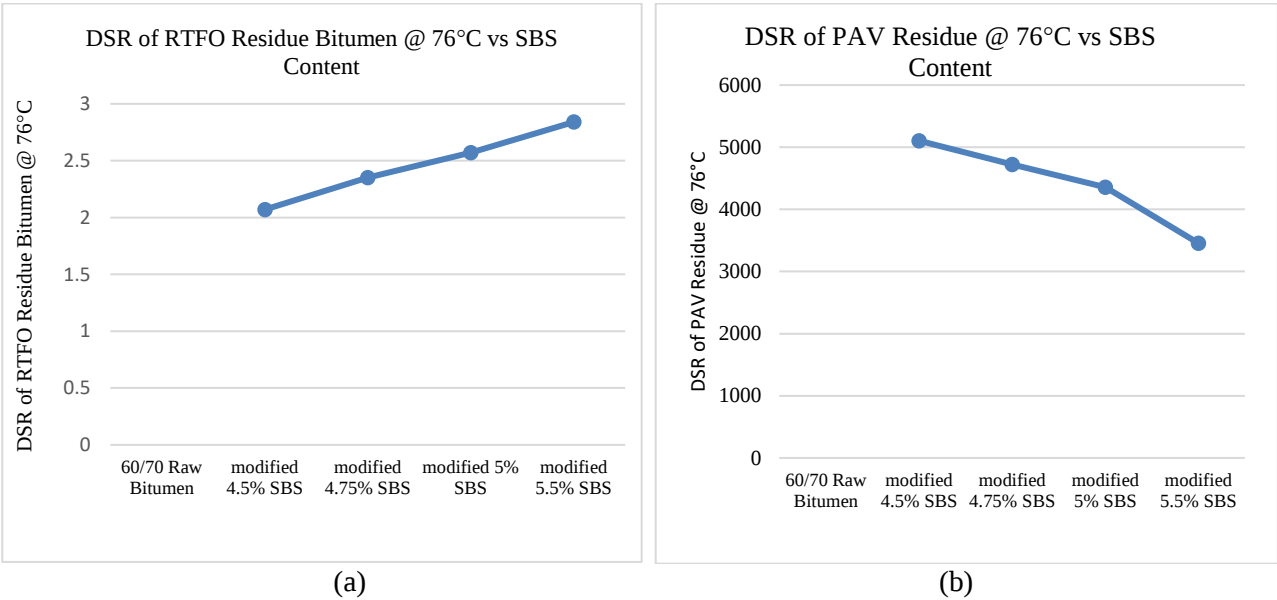


Figure 7. a) Dynamic Shear Rheometer (DSR) Results of RTFO Residue at 76°C: Variation of $G/\sin(\delta)$ with SBS Content; b) Dynamic Shear Rheometer (DSR) Results of PAV Residue at 76°C: Effect of SBS Content on Viscoelastic Properties.

3.2.2. Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) Tests

From [Figure 8](#), we found that all modified bitumen samples, except the one with 4.5% SBS content, performed well in cold temperature tests. They showed excellent resistance to permanent deformation, with the 5.5% SBS sample achieving a value of 0.21 kPa in the Non-Recoverable Creep Compliance test. As SBS content increases, the non-recoverable creep compliance decreases, indicating

that the bitumen becomes stiffer and more resistant to deformation. In other words, there is a negative correlation between SBS content and creep compliance, so a lower value signifies better resistance to permanent deformation under stress. This suggests that higher SBS content improves the bitumen's resistance to rutting.

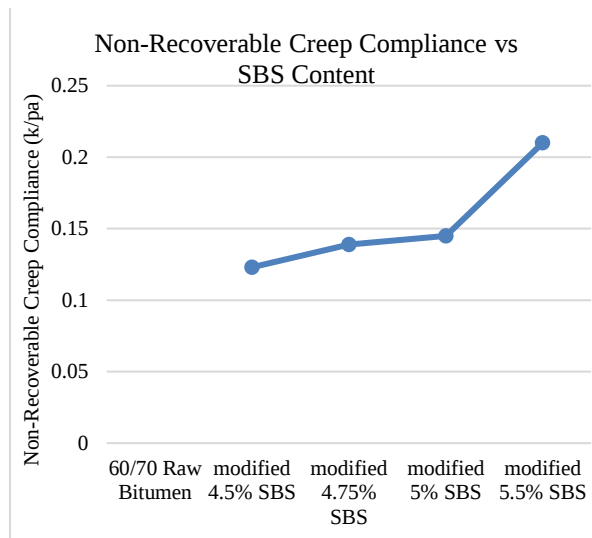


Figure 8. Non-Recoverable Creep Compliance (Jnr) vs. SBS Content: Impact of SBS Modification on Elastic Recovery and Rutting Resistance of Bitumen.

Table 1. Summary of test results.

SL	Test Name	Standard Test/Practice Code (AASHTO)	Unit	Standard Test Limit	60/70 Raw Bitumen	Modified with 4.5% SBS	Modified with 4.75% SBS	Modified with 5% SBS	Modified with 5.5% SBS
						Sample 1	Sample 2	Sample 3	Sample 4
1	Sampling of bitumen	T 168				-			
2	Flash Point (Cleveland Open Cup)	T 48	°C	230	280	304	312	319	350
3	Ductility at 25°C	T 51	cm	>100	110	-			
4	Softening Point Test R & B	T 53	-	48-56	52	-			
5	Penetration at 25°C, 100g, 5sec	T 49	-	60-70	62	-			
6	Viscosities can be tested between 0.01 Pa s (0.1 poise) and 200 Pa s (2000 poise) at 135°C	T 316	cP	-		1750	1800	1850	1923
			$\eta_{pmv} / \eta_{bitumen}$			4.73	5.23	5.66	6.33
7	Viscosities can be tested between 0.01 Pa s (0.1 poise) and 200 Pa s (2000 poise) at 165°C	T 316	cP			575	643	675	699
			$\eta_{pmv} / \eta_{bitumen}$			4.6	4.83	5.11	5.39
8	DSR of Original Bitumen (Dynamic Shear Modulus) 76 °C	T 315	kPa	>1	-	1.31	1.76	1.95	2.10
9	RTFO (Mass Change)	T 240	%	< 1.0	-	0.19	0.15	0.13	0.16
10	DSR of RTFO Residue Bitumen (Dynamic Shear Modulus) @ 76 °C	T 315	kPa	>2.2	-	2.07	2.35	2.57	2.84
11	PAV	R 28	°C			110			
12	DSR of PAV Residue (Dynamic Shear Modulus)	R 29	kPa	<5000	-	5104	4721	4357	3456
13	Creep Stiffness S, Max at 300Mpa and m-value, min .300 Test temp @60s	M 313	°C	-	-12	-18	-18	-18	-18
14	Non-Recoverable creep Compliance	T 350	k/Pa	<0.5	-	0.123	0.139	0.145	0.21
						Not Ok	Ok	Ok	Ok

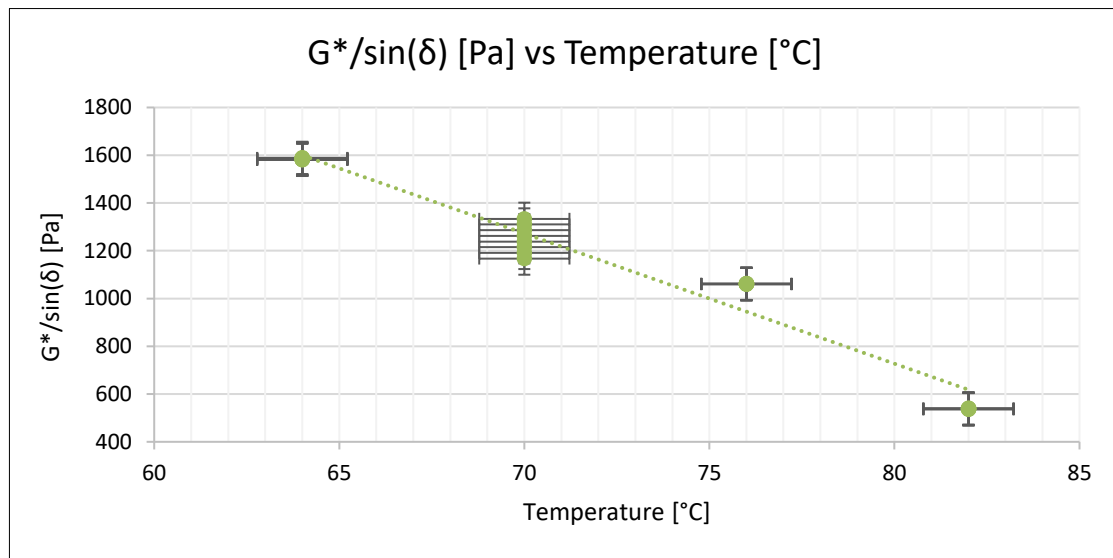


Figure 9. $G^*/\sin(\delta)$ [Pa] vs Temperature

3.3. Viscoelastic Properties

In [Figure 6](#), the plot of $G^*/\sin(\delta)$ against temperature highlights the viscoelastic behavior of the bitumen blend with 4.75% SBS content. It shows how the complex shear modulus (G^*) changes with temperature, emphasizing the improved thermal response of the material. This enhanced thermal behavior, due to the addition of SBS, is crucial for applications in regions with wide temperature fluctuations. The Bending Beam Rheometer (BBR) tests further confirm the blend's excellent low-temperature performance at -18°C , making it suitable for areas with severe freezing conditions.

From [Figure 10 a](#), we observe that as SBS content increases, the creep stiffness decreases, indicating the

bitumen becomes more flexible and better able to recover after stress. This improvement in flexibility and recovery helps prevent cracking at low temperatures, reducing the material's susceptibility to thermal cracking.

From [Figure 10 b](#), the Dynamic Shear Modulus (DSR) of the bitumen increases with higher SBS content, showing a positive correlation. This means the bitumen becomes stiffer and more resistant to shear deformation at 76°C , enhancing its high-temperature performance and overall resistance to rutting..

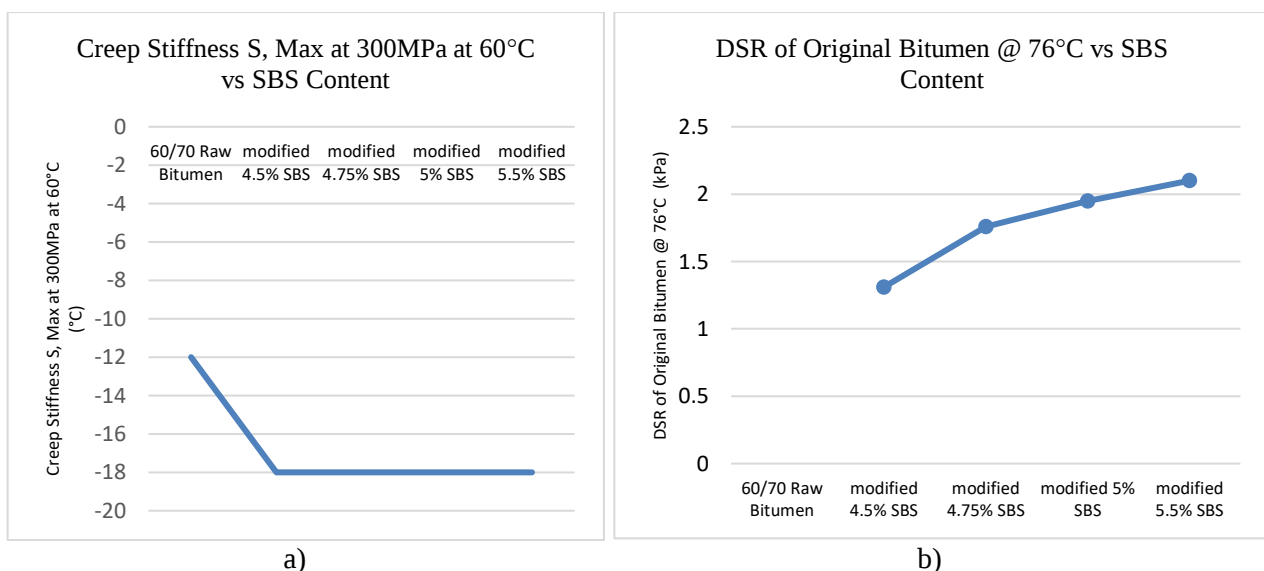


Figure 10. : a) Creep Stiffness of SBS-Modified Bitumen at Low Temperatures (-18°C); b) Effect of SBS Content on Viscoelastic Properties of Bitumen: $G^*/\sin(\delta)$ at 76°C .

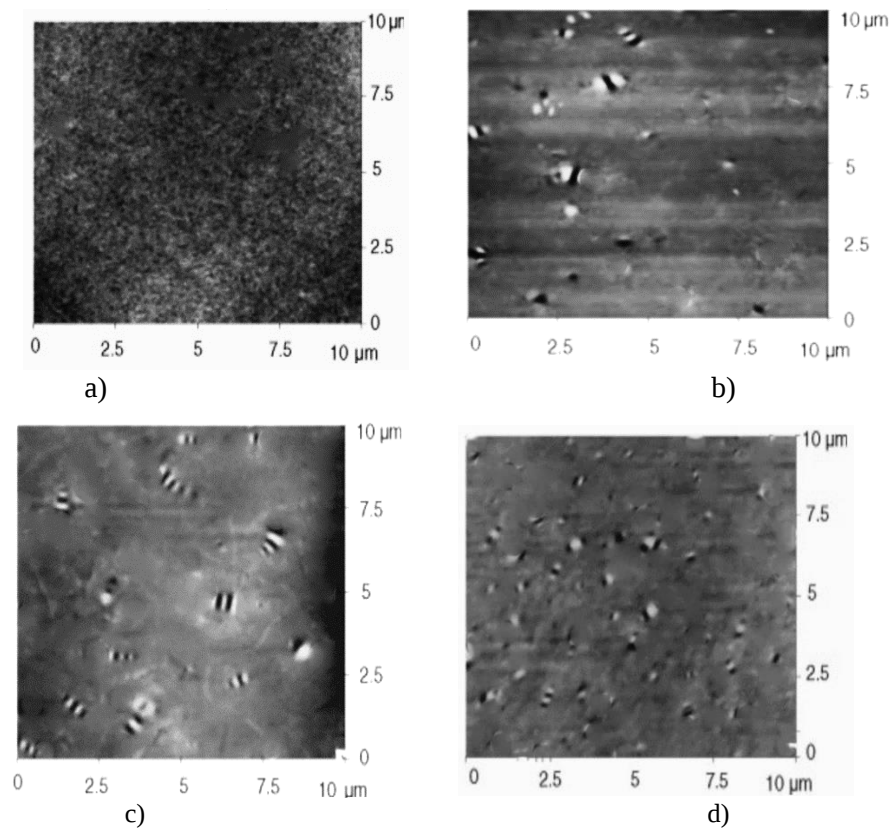


Figure 11. : a) High-resolution AFM images showcasing the pristine surface characteristics of unaged PG76 asphalt material containing 4.75% SBS.; b) Two-dimensional AFM images offer an in-depth visual analysis of the topographical attributes of unaged PG76 bitumen containing 4.75% SBS.; c) The surface characteristics of unaged PG76 asphalt are depicted, providing a reference point; d) The results of pressure aging vessel (PAV) aging on PG76 bitumen 4.75% SBS, with aging conditions set at 1200 hours, 60°C, and an air pressure of 2.1 megapascals.

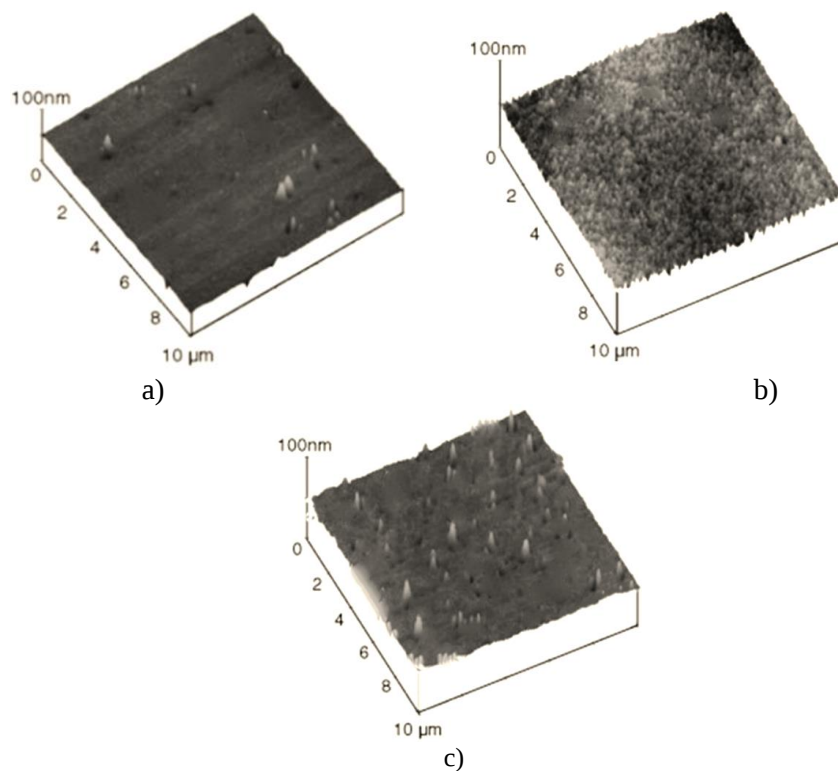


Figure 12. : a) Atomic Force Microscopy (AFM) images depicting the surface morphology of unaged PG76 asphalt material with 4.75% SBS; b) High-resolution AFM images showcasing the topographical features of unaged PG76 asphalt material with 4.75% SBS; c) AFM images capturing the surface changes resulting from pressure aging vessel (PAV) aging of PG76 asphalt, conducted at specific conditions: 1200 hours, 60 degrees Celsius, and an air pressure of 2.1 megapascals.

3.4. Microstructural Analysis Via Atomic Force Microscopy (AFM)

Atomic Force Microscopy (AFM) provided detailed insights into the surface and microstructural properties of unaged and aged PG 76-18 asphalt containing 4.75% SBS. For the unaged specimen, [Figure 7](#) showcases pristine surface characteristics. Post-aging, however, the same figure reveals the emergence of bumblebee-like structures, indicative of enhanced crosslinking. This crosslinking, observed after exposing the bitumen to pressure aging vessel (PAV) conditions (1200 hours at 60°C and 2.1 megapascals), suggests significant

improvements in the mechanical properties of the material, making it more durable and resilient under various loading conditions. [Figure 8](#) further compares the surface morphology between the unaged and aged asphalt, illustrating significant changes due to aging which affect the asphalt's durability and performance. This comparison underscores the impact of the aging process on the asphalt's surface properties, crucial for assessing its long-term usability.

3.5. Comparison of Surface Morphology

As shown in [Table 1](#), the flash point and viscosity of bitumen increase with rising SBS content, reflecting enhanced thermal stability and resistance to flow. For example, bitumen with 5.5% SBS achieves a flash point of 350°C and a viscosity of 1923 cP at 135°C, significantly outperforming the unmodified sample. [Figure 6\(a\)](#) illustrates a positive linear relationship between SBS content and flash point, emphasizing improved thermal stability. Similarly, [Figure 6 \(b\)](#)

demonstrates that viscosity at 135°C increases with SBS content, indicating better high-temperature performance. In [Figure 6 \(c\)](#), a comparable positive trend is observed at 165°C, though the increase is less pronounced due to the higher temperature. These results underline the effectiveness of SBS modification in enhancing the bitumen's durability and operational temperature range.

3.6. Optimization for Regional Conditions

The comprehensive testing and analysis led to the selection of the 60/70 penetration grade bitumen sample with 4.75% SBS as the optimal blend. This choice was based not only on its superior

performance across various tests but also on its economic viability, making it a preferred material for road construction in South Asian climates.

4. COCNLUSION

The research findings affirm that a Polymer Modified Bitumen (PMB) blend with 4.75% Styrene-Butadiene-Styrene (SBS) polymer content meets the rigorous PG 76-18 specifications, achieving an optimal balance of performance and cost-effectiveness for road construction in South Asian climates. Atomic Force Microscopy (AFM) provided crucial insights into the microstructural changes within the bitumen, demonstrating how SBS modifications enhance the material's phase structure and surface morphology. From pristine surfaces in unaged asphalt to visible enhancements and aging markers in aged samples, AFM images have vividly illustrated the beneficial effects of SBS on bitumen's durability and mechanical integrity.

The PMB samples, particularly with 4.75% polymer content, consistently demonstrated robust

performance in Dynamic Shear Rheometer (DSR) tests and exhibited remarkable stability even after undergoing rigorous aging processes like the Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) tests. This study not only highlights the superior resistance of the optimized PMB to aging effects but also underscores its practical viability for enhancing road infrastructure in regions prone to severe temperature fluctuations.

This research sets a new benchmark for high-performance, durable road materials suited to the environmental and economic contexts of South Asia, thus paving the way for future advancements in civil engineering materials.

Abbreviation

1. PMB - Polymer-Modified Bitumen
2. PG - Performance Grade
3. SBS - Styrene-Butadiene-Styrene
4. SHRP - Strategic Highway Research Program
5. EVA - Ethylene Vinyl Acetate
6. HMA - Hot-Mix Asphalt
7. RAP - Reclaimed Asphalt Pavement
8. AFM - Atomic Force Microscopy
9. RTFO - Rolling Thin Film Oven
10. PAV - Pressure Aging Vessel
11. NRC - Non-Recoverable Creep Compliance
12. BBR - Bending Beam Rheometer
13. GDSUTP- Greater Dhaka urban Transport project

14. BRT -Bus Rapid Transit

15. BRRL - Bangladesh Road Research Laboratory
16. AASHTO - American Association of State Highway and Transportation Officials

Nomenclature

1. Viscosity (η) - η
2. Centipoise (CPS) - cP
3. Complex Shear Modulus - G^*
4. Phase Angle - δ
5. Pascal - Pa
6. Micron - μm
7. Pascal-second - Pa s
8. Degree Celsius - $^{\circ}\text{C}$

FUNDING/SUPPORT

Not mentioned any Funding/Support by authors.

ACKNOWLEDGMENT

I would like to express my sincere gratitude to the Bangladesh Road Research Laboratory (BRRL) and the personnel of the GDSUTP-BRT Project Laboratory for their invaluable support and for granting me access to their facilities. I also wish to acknowledge BCL Associates Limited for their continued support throughout this research.

AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

5. REFERENCES

- [1] Airey GD. Fundamental binder and practical mixture evaluation of polymer modified bituminous materials. *International Journal of Pavement Engineering*. 2004;5(3):137–151. [View at Google Scholar](#); [View at Publisher](#).
- [2] Zorn S, Mehta Y, Dahm K, Batten E, Nolan A, Dusseau R. Rheological Properties of the Polymer Modified Bitumen with Emphasis on SBS Polymer and Its Microstructure. 2011 May 23;41–48. [View at Google Scholar](#); [View at Publisher](#).
- [3] Kumar K, Singh A, Maity SK, Srivastava M, Sahai M, Singh RK, et al. Rheological studies of performance grade bitumens prepared by blending elastomeric SBS (styrene butadiene styrene) co-polymer in base bitumens. *Journal of Industrial and Engineering Chemistry*. 2016 Dec 25;44:112–117. [View at Google Scholar](#); [View at Publisher](#).
- [4] Shih RS, Kuo SW, Chang FC. Thermal and mechanical properties of microcellular thermoplastic SBS/PS/SBR blend: effect of crosslinking. *Polymer (Guildf)*. 2011 Feb 3;52(3):752–759. [View at Google Scholar](#); [View at Publisher](#).
- [5] Saboo N, Kumar P. Use of flow properties for rheological modeling of bitumen. *International Journal of Pavement Research and Technology*. 2016 Jan 1;9(1):63–72. [View at Google Scholar](#); [View at Publisher](#).
- [6] Ishaq MA, Venturini L, Giustozzi F. Correlation Between Rheological Rutting Tests on Bitumen and Asphalt Mix Flow Number. *International Journal of Pavement Research and Technology*. 2022 Nov 1;15(6):1297–316. [View at Google Scholar](#); [View at Publisher](#).
- [7] Oluwasola EA, Hainin MR, Idham MK, Abayomi M. WORKABILITY AND RHEOLOGICAL PROPERTIES OF EVA-MODIFIED BITUMEN COMPARED WITH PG 76 BINDER. *Jurnal Teknologi*. 2018 Apr 29;80(4):117–24. [View at Google Scholar](#); [View at Publisher](#).
- [8] Solouki A, Muniandy R, Hassim S, Kheradmand B. Rheological Property Investigation of Various Sasobit-modified Bitumen. *Petroleum Science and Technology*. 2015;33(7):773–9. [View at Google Scholar](#); [View at Publisher](#).
- [9] Oner J, Sengoz B, Rija SF, Topal A. Investigation of the rheological properties of elastomeric polymer-modified bitumen using warm-mix asphalt additives. *Road Materials and Pavement Design*. 2017 Sep 3;18(5):1049–66. [View at Google Scholar](#); [View at Publisher](#).
- [10] Vargas MA, Sánchez-Sólis A, Manero O. Asphalt/polyethylene blends: Rheological properties, microstructure and viscosity modeling. *Construction and Building Materials*. 2013 Aug 1;45:243–50. [View at Google Scholar](#); [View at Publisher](#).
- [11] Kaya D, Topal A, McNally T. Relationship between processing parameters and aging with the rheological behaviour of SBS modified bitumen. *Construction and Building Materials*. 2019 Oct 10;221:345–350. [View at Google Scholar](#); [View at Publisher](#).
- [12] Liu Q, Wu J, Qu X, Wang C, Oeser M. Investigation of bitumen rheological properties measured at different rheometer gap sizes. *Construction and Building Materials*. 2020 Dec 30;265:120287. [View at Google Scholar](#); [View at Publisher](#).
- [13] Airey GD, Rahimzadeh B. Combined bituminous binder and mixture linear rheological properties. *Construction and Building Materials*. 2004 Sep 1;18(7):535–548. [View at Google Scholar](#); [View at Publisher](#).
- [14] Willis JR, Taylor A, Tran NH, Kluttz B, Timm DH. Laboratory

evaluation of high polymer plant-produced mixtures. *Road Materials and Pavement Design*. 2012;13(April 2013):260–280. [View at Google Scholar](#); [View at Publisher](#).

[15] Sengoz B, Isikyakar G. Evaluation of the properties and microstructure of SBS and EVA polymer modified bitumen. *Construction and Building Materials*. 2008;22(9):1897–1905. [View at Google Scholar](#); [View at Publisher](#).

[16] Zhou Z, Gu X, Jiang J, Ni F, Jiang Y. Fatigue cracking performance evaluation of laboratory-produced polymer modified asphalt mixture containing reclaimed asphalt pavement material. *Construction and Building Materials*. 2019;216:379–389. [View at Google Scholar](#); [View at Publisher](#).

[17] Gorkem C, Sengoz B. Predicting stripping and moisture induced damage of asphalt concrete prepared with polymer modified bitumen and hydrated lime. *Construction and Building Materials*. 2009;23(6):2227–2236. [View at Google Scholar](#); [View at Publisher](#).

[18] Bernier A, Zofka A, Yut I. Laboratory evaluation of rutting susceptibility of polymer-modified asphalt mixtures containing recycled pavements. *Construction and Building Materials*. 2012;31:58–66. [View at Google Scholar](#); [View at Publisher](#).

[19] Sengoz B, Isikyakar G. Analysis of styrene-butadiene-styrene polymer modified bitumen using fluorescent microscopy and conventional test methods. *Journal of Hazardous Materials*. 2008;150(2):424–432. [View at Google Scholar](#); [View at Publisher](#).

[20] Joohari IB, Giustozzi F. Hybrid polymerisation: An exploratory study of the chemo-mechanical and rheological properties of hybrid-modified bitumen. *Polymers (Basel)*. 2020;12(4):945. [View at Google Scholar](#); [View at Publisher](#).

[21] Zhu J, Birgisson B, Kringos N. Polymer modification of bitumen: Advances and challenges. *European Polymer Journal*. 2014;54:18–38. [View at Google Scholar](#); [View at Publisher](#).

[22] Zorn S, Mehta Y, Dahm K, Batten E, Nolan A, Dusseau R. Rheological Properties of the Polymer Modified Bitumen with Emphasis on SBS Polymer and Its Microstructure. 2011 May 23;41–48. [View at Google Scholar](#); [View at Publisher](#).

[23] Ouyang Q, Xie Z, Liu J, Gong M, Yu H. Application of Atomic Force Microscopy as Advanced Asphalt Testing Technology: A Comprehensive Review. *Polymers*. 2022;14(14):2851. [View at Google Scholar](#); [View at Publisher](#).

[24] Kaya Ozdemir D, Topal A, McNally T. Relationship between microstructure and phase morphology of SBS modified bitumen with processing parameters studied using atomic force microscopy. *Construction and Building Materials*. 2021 Jan 25;268:121061. [View at Google Scholar](#); [View at Publisher](#).

[25] Rajapaksha M. MC, Athukorallage B, Senadheera S, James D. Temporal and spatial temperature predictions for flexible pavement layers using numerical thermal analysis and verified with large datasets. *Case Studies in Construction Materials*. 2023 Jul 1;18:e02008. [View at Google Scholar](#); [View at Publisher](#).

[26] India Meteorological Department. Home | India Meteorological Department [Internet]. [cited 2024 Apr 30]. [View at Google Scholar](#); [View at Publisher](#).

[27] Weather in Dhaka in January 2024 (Dhaka Division) - Detailed Weather Forecast for a Month [Internet]. [cited 2024 Apr 29]. [View at Google Scholar](#); [View at Publisher](#).

[28] LTPP InfoPave - LTPP Climate Tool [Internet]. [cited 2024 May 1]. [View at Google Scholar](#); [View at Publisher](#).

[29] Sri Lanka Record High and Low Temperature (Celsius) Map and List - Updated April 2024 [Internet]. [cited 2024 Apr 29]. [View at Google Scholar](#); [View at Publisher](#).

[30] AASHTO M 323 [Internet]. 43rd ed. Vol. PART 2A TESTS. American Association of State Highway and Transportation Officials (AASHTO); 2023 [cited 2024 May 1]. [View at Google Scholar](#); [View at Publisher](#).